COR1 Engineering Test Unit Measurements at NRL, March 2003

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1 Introduction

Previous testing activity in the COR1 was performed at the NCAR/HAO Vacuum Tunnel Facility in Boulder, Colorado. However, the flight instruments will be characterized at a similar facilty at NRL, as part of the full SCIP package. Therefore, it was decided to take the COR1 ETU to NRL to practice the procedures which will be used for flight. Here we report on the results of those tests, which took place between March 10 and April 2, 2003.

2 Description of the facility

The vacuum facility at NRL consists of three sections. The "dirty room" contains the bulk of the vacuum tank, the mechanism controls, and the lamp. The other end of the tank, where the instrument is installed, is in the "clean room", which operates at a cleanliness level of 100 at one end, to 1000 at the other end. However, during the test, the room had not been cleaned to that high level, and was probably closer to a cleanliness level of 10,000. Also in the clean room is a long, vibration-isolated, optical bench. Between the two is the "grey room", which serves as an operations room for the GSE computer, as a cleaning and staging area for the clean room, and as a gowning area. Foot covers were required for entering the grey room—gloves may also be required in the future. Double-gloving was standard procedure in the clean room.

Passage from the grey room to the clean room is through an airlock-style air shower. (However, the air shower was not operational during the tests.) There is also a pass-through for equipment. All equipment was taken into the clean room through the pass-through, except for the ETU itself. The ETU was taken in through a set of double doors at the back of the clean room, with a pass-off between two gloved people outside the clean room, and two fully gowned people inside the clean room.

Computers were installed in the grey room, and the cabling was passed through one of two different routes. When the ETU was on the optical bench, the cabling was passed through a small slit cut into a covered slot just below the pass-through. When the ETU was inside the vacuum tank, the cabling was passed through a hole where a vacuum feed-through would normally be, into the dirty room, and through another slot into the grey room. In this latter case, wadded cloths were used to plug up the holes that the cables were passed through. The total cable length was similar in both cases.

Because the clean room was also being used as a darkroom, all the windows were covered over. That made it impossible for people outside the clean room to see in, and vice versa. All communication was done with hand-held walkie-talkies, or by people walking between the clean room and grey room. Communications was difficult with the walkie-talkies, and on occasion the person working inside the cleanroom, and the person operating the GSE in the grey room, would get out of step with each other. Procedures needed to be worked out to keep this from happening.

3 Optical differences between HAO and NRL

In many ways, the facilities at HAO and NRL are very similar. Both are long vacuum tunnels, with the instrument being tested at one end, and an aperture defining the "solar" image at the other end, with no optics in between to cause scattering. The way that the aperture is illuminated, however, is quite different for the two facilities. At HAO, an altitude-azimuth mirror system directs sunlight onto a Fresnel lens, which concentrates the light onto a diffuser. A large lens directs the light from the diffuser down the tunnel, through the aperture. With this setup, the aperture is illuminated quite uniformly, but the illumination level varies with the weather and time-of-day. To calibrate out the varying light level, a photodiode with a proper bandpass filter was placed next to the instrument. This was possible, because the beam coming down the tunnel was large enough to easily encompass both the instrument aperture and the diode.

A major disadvantage of the HAO approach is that the beam ends up being significantly fainter than the Sun, because of the broad spreading caused by the diffuser. The NRL approach eliminates the diffuser, in favor of a much brighter beam. A bright xenon arc lamp (1500 Watts) is used instead of the Sun, freeing the facility from weather variations, and providing a fairly steady source. A projection lens in the lamp housing is used to focus the light onto a small aperture. A collimating lens then focuses the light from this aperture, through the chamber window and the ultimate limiting aperture, and onto a spot a little bit behind the front aperture of the COR1 instrument. This spot is very small, and the light only just covers the front of the instrument. That made it impossible to place the existing diode assembly next to the COR1 aperture.

Figure 1 shows an image of the source as seen by the COR1 instrument. This image was taken by placing both a 4.0D and 2.0D neutral density filter over the detector, for a total extinction of 10^{-6}. The source is fairly well illuminated over the entire aperture, but there is some structure to the illumination pattern. To explore the flickering of the source, we took a series of 10 images in a row. The image on the right in Figure 1 shows the pixel-by-pixel standard deviation. We found that the total brightness integrated over the source varied by about 0.5% RMS, but that local variations could be much higher, by as much as an order of magnitude.

One question is whether the illumination pattern at the instrument varied uniformly over the instrument aperture, or whether there were localized variations over different parts of the aperture. The distinction is important if a photodiode could be fit in just next to the aperture. We did perform some measurements with the photodiode in front of the aperture, and found that the light flickered at the rate of 0.42%. From that we deduce that locating a photodiode right next to the aperture would be effective, if it could be done.

Another suggested location for a photodiode was at the vacuum chamber window, just outside the defining aperture. However, the local variations demonstrated in Figure 1 were easily visible to the eye there, so that placing a photodiode there would not help.

The challenge, then, is to monitor the entire beam going down the tunnel, and not just a portion of the beam. One possibility is to use a beam splitter just past the small aperture in front of the

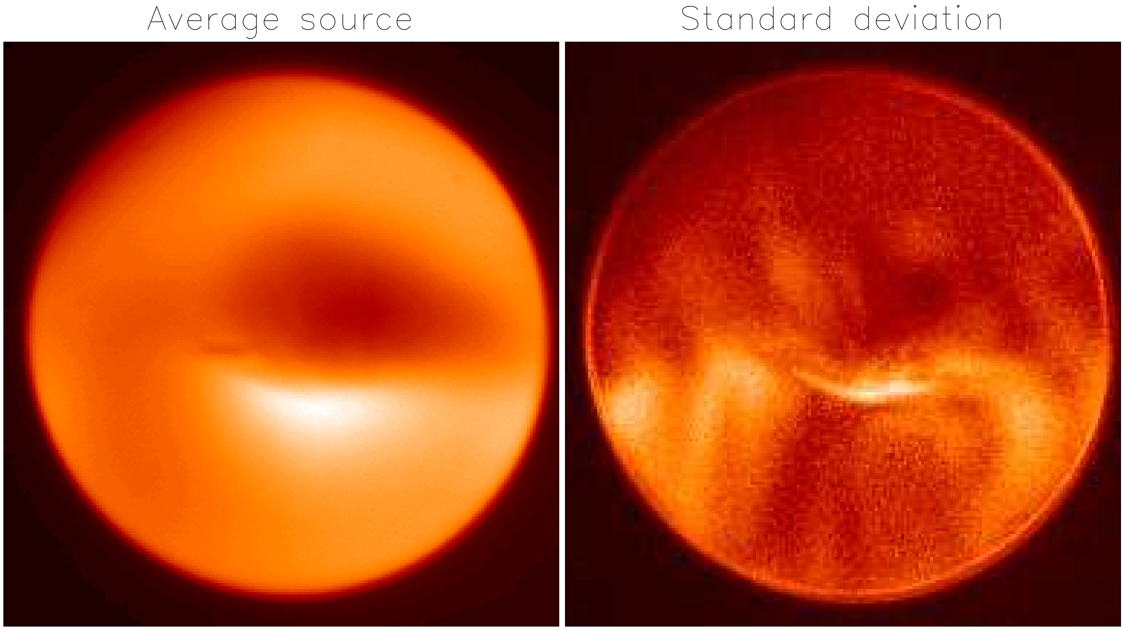

Figure 1: On the left is an image of the source aperture as seen through a 6.0D (10^{-6}) neutral density filter. The image on the right is the standard deviation derived from a series of images, demonstrating the flickering of the source.

lamp, to direct a part of the beam into a diode. The beam splitter would need to be large enough to collect all of the beam at that point. A lens could then be used to focus the beam onto a diode.

4 Facility problems

The NRL facility had been mothballed for a long time, and understandably a number of problems were encountered trying to use it. The first problem occured when the control cable was run over while the vacuum chamber was being opened. From then on, the vacuum chamber was stuck in the open position. This did not seriously impact our measurements—we simply turned off the room lights.

Three motors are used to control the height of the instrument bench within the vacuum chamber, two in the front, and one in the rear. Moving all three motors simultaneously moves the entire instrument up or down. Moving just the motor in the back gives pitch control. In principal, one can also move the two front motors in opposite directions to roll the instrument, but it was never intended to do this. However, it turned out that one of the two front motors was sticking, and the instrument was being rolled unintentionally. This happened twice. The first time was only a small amount, and the cause was not recognized. The second time was more serious, and pulled a connector off the polarizer motor, without however disconnecting the actual wires to the polarizer.

We also had problems maintaining a continuous supply of ultrapure GN_2 for purging the instrument. In part this was because we hadn't informed NRL sufficiently far enough in advance that we would be needing GN_2. Also, there was a lot of miscommunication between NRL and GSFC about who was changing out the bottles. Once, the GN_2 bottle was allowed to run dry, and on another occasion the bottle was turned off just hours before it was about to run dry. Because of the difficulty of getting GN_2, we only purged at a rate of 1 $\mathrm{ft}^3/\mathrm{hr}$ instead of the normal 2 $\mathrm{ft}^3/\mathrm{hr}$.

There were two problems that we knew about before shipping the instrument to NRL: the power supply for the xenon lamp needed to be repaired, and the bracket to hold the ETU inside the vacuum tank was not completed. Since the initial tests were scheduled for outside the vacuum tank, and since neither presented a contamination risk, it was decided to not hold up the schedule until these problems were resolved.

5 Optical bench test results

The first tests were scheduled to run on the optical bench outside of the vacuum tank. The advantage of working on the optical bench is that it's easier to access and adjust the instrument. The disadvantage is that one cannot make use of the steering capability one has in the vacuum tank. We did not actually pump down the vacuum chamber for the ETU tests, but for the flight model the vacuum chamber has the advantage that there is less risk of contaminating the objective lens.

5.1 NRL collimated source

Earlier, with the second COR1 breadboard, we had borrowed a collimated source from NRL, and used it in the Schlieren room at Goddard to explore the bright rings around the edge of the occulter.

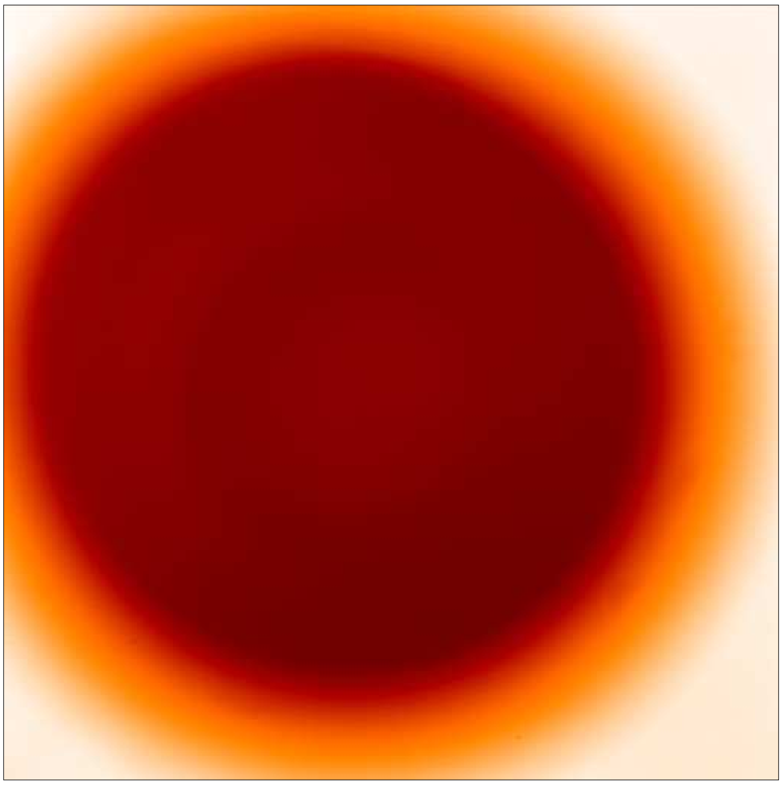

Figure 2: Image of the NRL light box, showing the shadow of the occulter.

This NRL source projects an image with an angular diameter similar to that of the Sun at infinity. A Goddard-supplied adjustable iris mounted in front of the source allows the source to be operated in a similar manner to the vacuum tank.

It was intended to use the NRL source on the optical bench before going into the vacuum tank. However, the COR1 ETU did not have any fine pointing capability, nor did the NRL source. Without any adjustment features, we were unable to coalign the source and instrument well enough to put the source image completely on the occulter. Since the test would be done better in the vacuum tank, it was decided to not pursue this further.

5.2 Light box

A very useful piece of test equipment that was supplied for us was a “light box”. This was a box with a window of opal glass which produced a faint, but uniform glow. Figure 2 shows an image taken with the light box, which is highly similar to what one would see through the window in the door. We were told that the amount of light being produced was approximately $2 \times 10^{-9} B_{\odot}$. Unfortunately, the light box couldn't be found on the day we took the photometer into the cleanroom. The signal seen in the unocculted sections was 672 ± 7 DN/s. I don't have sufficient information about the optical components in the ETU to make an exact calculation, but I can estimate that this signal level is consistent with a light level of $2 \times 10^{-9} B_{\odot}$.

5.3 Partial polarization

One of the pieces of test equipment which NRL provided was a partial polarizer. This is a barrel with two pieces of glass, each held at about 45° to the normal, in opposite directions. When illuminated from behind by a uniform "light box", the result is a partially polarized source. We measured a uniform polarization level of ∼12.5% outside of the occulter shadow, with a uniform direction of polarization. According to Clarence Korendyke, this is the correct value in our bandpass. When we rotated the partial polarizer by ∼90°, the measured polarization direction also rotated by the same amount.

5.4 Resolution

One of the tests involved using an NRL-supplied collimator with an Air Force resolution test target to test the focus of the instrument. We were never able to get the high resolution images that were seen in the HAO tests. We tried finding the best focal position twice, both before going into the vacuum tank, and after coming out. One possibility is that the images were being degraded by the polarizer, which wasn't installed for the HAO resolution tests. Figure 3 shows an example of a small section of the Air Force target image, as a function of polarizer angle. We found that the image shifted position as the polarizer was rotated. This was not a surprising result, given the sensitivity of the image position to the "wedge" of the polarizer.

However, an unexpected result was that the point spread function also varied with polarizer angle, so that at some angles the horizontal bars were in best focus, while at other angles the vertical bars were in best focus, as demonstrated in Figure 3. We were never able to find a camera focus position where both the horizontal and vertical bars were in focus simultaneously. (During the HAO tests, both directions were simultaneously in focus.) It's not obvious from Figure 3, but watching the full rotation data as a movie, it appears that the data consists of an image plus a linear smear or "comet tail" coming off from the image, where the tail rotates 180° out of phase with the image. There also appears to be another superimposed image rotating by itself off to the side, possibly with its own tail.

The polarizer used in the ETU was an off-the-shelf item from the Oriel catalog, and is quite different from the one planned for flight. We will need to examine the Oriel polarizer to see if it's responsible for the poor resolution.

6 Vacuum chamber test results

The setup of the vacuum chamber is discussed in Section 3. The primary purpose of this test is to explore the scattered light properties of the instrument. We also looked at the ability of the focal plane mask to remove the bright rings around the edge of the occulter.

6.1 Focal plane mask test

The first test performed in the vacuum chamber was to examine the effect of the focal plane mask. During the HAO tests we were unable to align the smaller focal plane mask to completely cover the occulter image, and had to resort to the larger mask, and place it well away from the expected

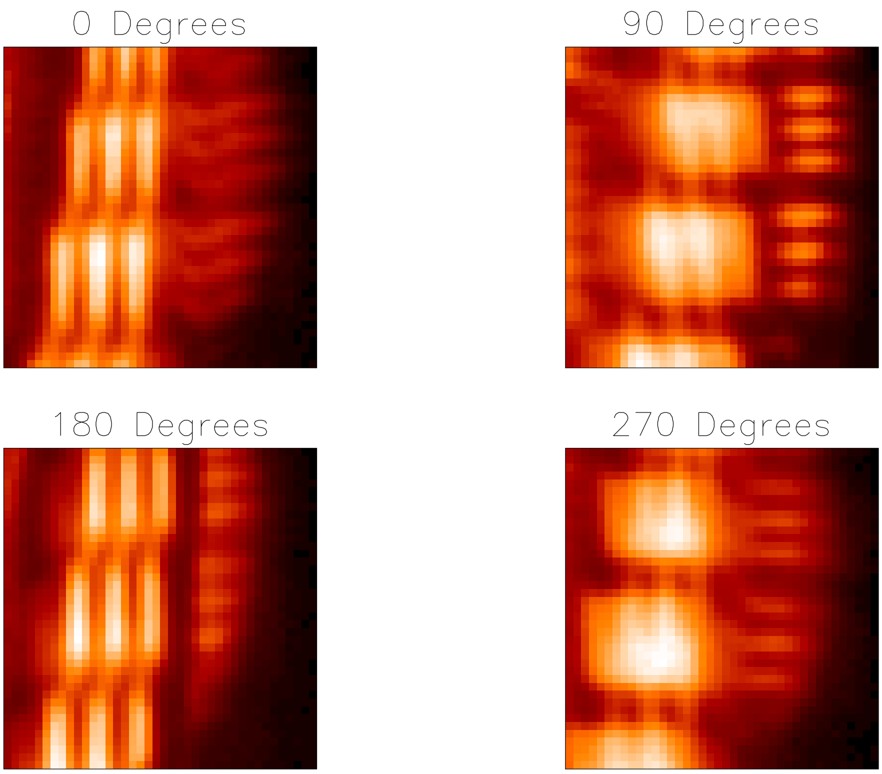

Figure 3: Images of a small section of an Air Force target at different polarizer angles, showing that the image shifts position as the polarizer rotates. The point spread function also rotates, causing the horizontal and vertical bars to come into focus at different times.

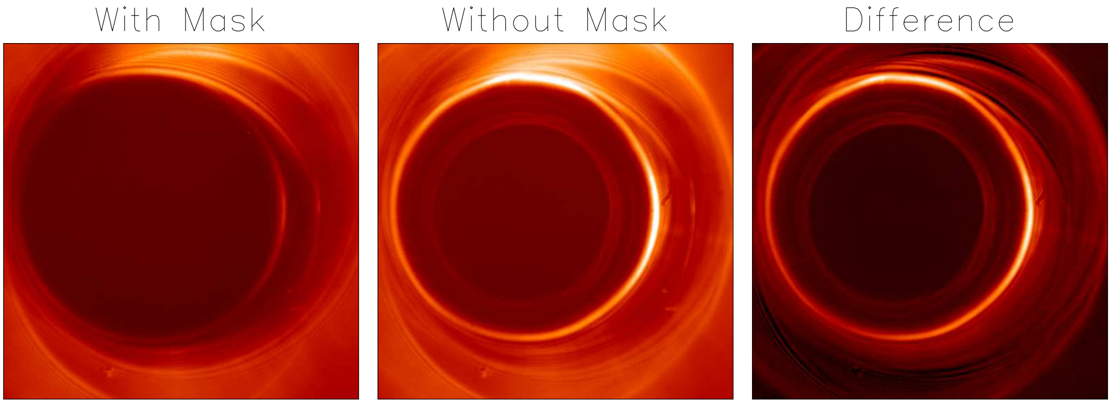

Figure 4: Images demonstrating the action of the focal plane mask. The first image is with the mask in place, while the second is without the mask. The third image is the difference between the first two images.

position. Later analysis revealed that the interior surfaces of doublet were made with the incorrect sign, which shifted the focal position and plate scale. Eric Mentzell adjusted for this error by moving doublet two along the rail, and then aligned the original (smaller) focal plane mask optically before the ETU was shipped from Goddard to NRL.

When it came time to test the mask in the NRL vacuum tank, the mask was not quite aligned, and some adjustment had to be made to completely cover the occulter image. It's not clear whether this was due to a problem in the original alignment technique at Goddard, or whether the optics had shifted during the shipment to NRL, and the subsequent testing on the optical bench. While on the optical bench, the focal plane mask had been unscrewed from its mount and then replaced, but it was felt that this should not change its alignment. The alignment knobs were not touched, but they weren't locked down either.

Figure 4 shows the action of the focal plane mask. The two bright rings around the edge of the occulter are effectively removed by the focal plane mask. (The outer ring is only partially visible in the images.) However, some structure remains between the inner and outer rings, even with the focal plane mask.

6.2 Scattered light

The camera used on the ETU during the NRL tests is different from the camera used during the earlier ETU and breadboard tests at HAO. The HAO camera was built in the lab from parts left over from the SOHO and SERTS programs, and was designed to operate cooled in a vacuum. However, because of contamination concerns, it was decided to make the ETU measurements at NRL in air. Therefore, the earlier breadboard camera was replaced with a commercial camera from Apogee, which could be operated cool in air. The Apogee camera, however, is only half of the size of the breadboard camera (12.3 mm vs. 21.5 mm). Doublet two was moved along the rail to change the plate scale, and recover most of the field of view that was available during the HAO tests.

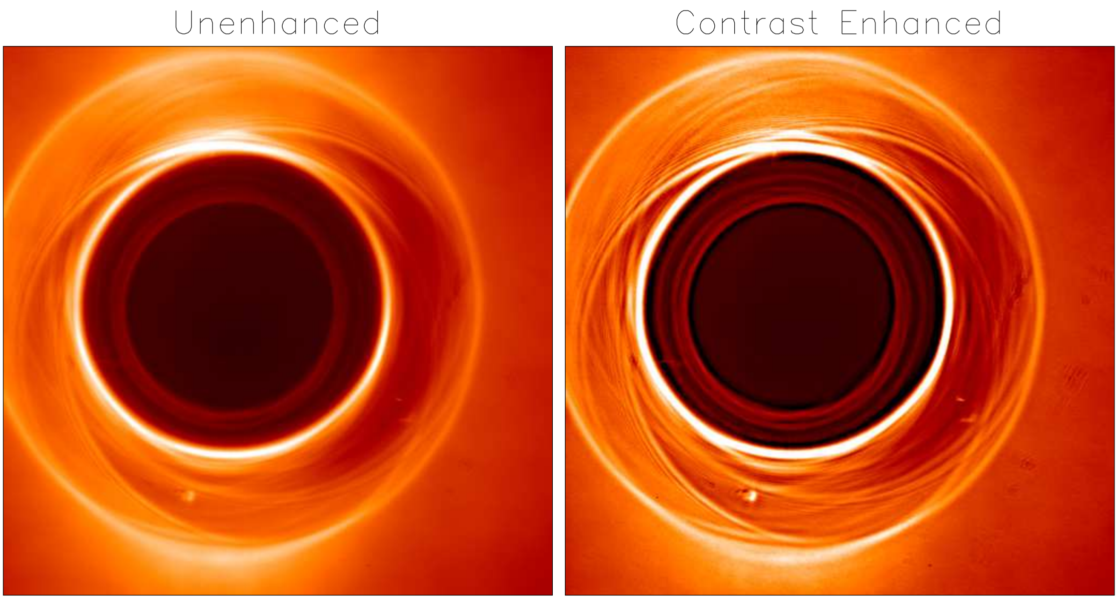

Figure 5: Image of the scattered light pattern seen during the NRL tests. The same image is shown on the right, with the contrast enhanced to bring out the fine features.

Figure 5 shows the scattered light pattern visible with this larger field of view. The main features are the two bright rings, which previous tests have identified with the umbra and penumbra of the occulter. There's also a much fainter set of rings inside the umbra, which was also seen during the previous HAO measurements. Between the two main rings are a number of arc-like features. These also have been seen before, but appear to be more prominent in these new measurements. Experimentation, however, shows that the prominence of these arcs depends on the camera location. For the NRL tests, the camera was located so that the source was in focus (Figure 1). Since the NRL source was $\sim$40 feet away, this position was significantly different from either infinity focus or the $\sim$100 feet distance that was used. When the two rings are closer together, as was the case at HAO, or would be the case for flight, these arc features are not as prominent compared to the two main rings. This is demonstrated in Figure 6. Thus, these data are to first order consistent with the data taken at HAO.

The effect on the scattered light pattern of the flickering in the source was examined. By intercomparing images, it was found that all parts of the image went up and down together. The standard deviation was about 0.5% RMS, which matches the level of flickering discussed in Section 3. Thus, it can be concluded that the flickering in the scattered light pattern depends on the total flickering integrated over the source, rather than the localized level of flickering at the source aperture.

6.3 Polarization

The flickering of the NRL source is significant at the level needed to determine the residual polarization of the ETU. In order to minimize the effects of the flickering, a large number of polarization

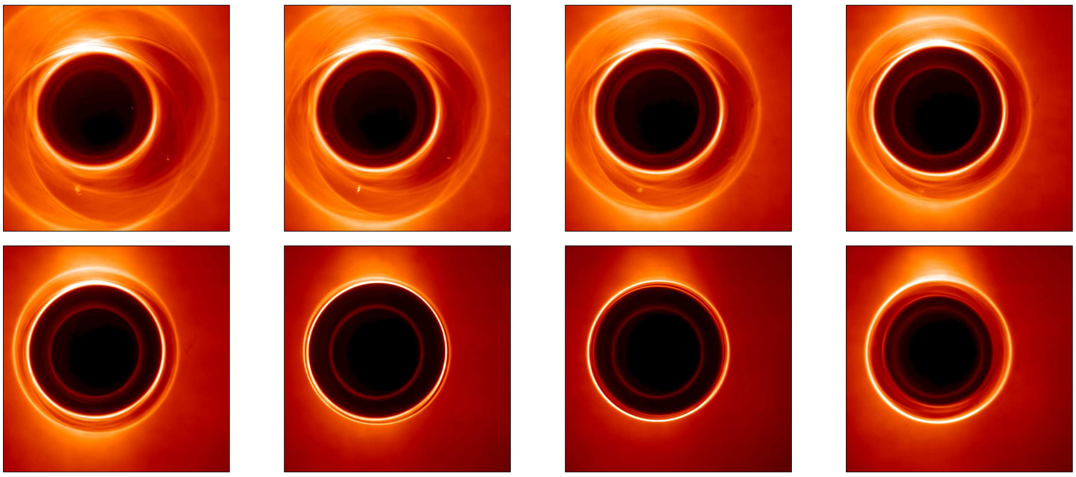

Figure 6: Images of the scattered light pattern at different camera positions along the rail.

angles were measured. We took a polarization sequence with angles 0°, 15°, 30°, ..., 360°, for a total of 25 polarization images. Each image pixel was then fitted to derive the total brightness B, polarized brightness pB, and polarization angle θ. Although the source is flickering during this time, one should still be able to extract out the sinusoidal variation characteristic of a polarization signal, so long as there are no long-term trends in the source brightness or other instrumental parameters.

The derived polarization data are shown in Figure 7. The results are very similar to those seen during the HAO tests: the bright rings are polarized at the 10–20% level, while the area outside the occulter shadow is polarized at the 0.5–3.0% level, with an average level of about 1.3%. The polarization angle shows a high degree of coherence, and (for the most part) varies in the expected way as a function of the azimuth around the occulter.

One way to test if the analysis is being affected by random variations in the source is to shuffle the observations into random order, and redo the analysis. When this was done, the measured polarization level is significantly lower, and the polarization angle is much more chaotic.

It was recently recognized that a small amount of wedge in the polarizer would cause the image to move around on the detector. We were able to measure this effect by taking a polarization series of the source (see Figure 1), and performing a cross-correlation analysis. The results are shown in Figure 8. It was theorized that the polarization results are simply an artifact of this image motion. To test this, the results from Figure 8 were used to correct the images before performing the analysis. While parts of the image with sharp gradients, such as the bright rings, did change some of the details of the polarization pattern, the results were essentially unchanged outside the occulter shadow. It appears that, in the unocculted parts of the image, the image gradient is too low for the image motion to induce the measured polarization signal.

6.4 Scattered light level

The data of Figure 1 can be used to establish an appropriate $B_\odot$ level for the source. There's a lot of variation in the source, but it's evident that the average level is somewhere around

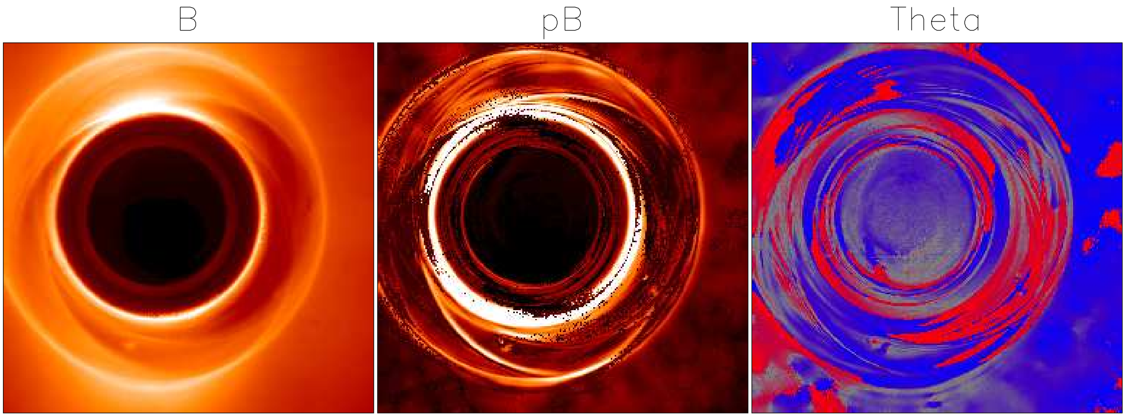

Figure 7: The derived brightness (B), polarized brightness (pB), and polarization angle (θ).

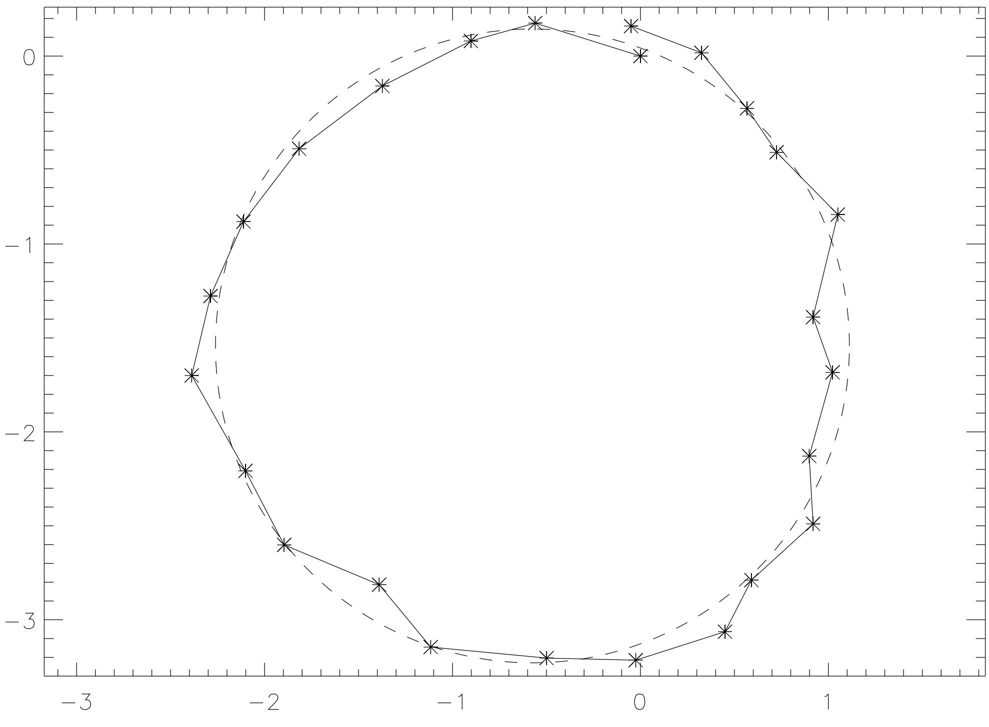

Figure 8: The relative shift of the image, in pixels, for a series of polarization angles. A circular fit is also shown.

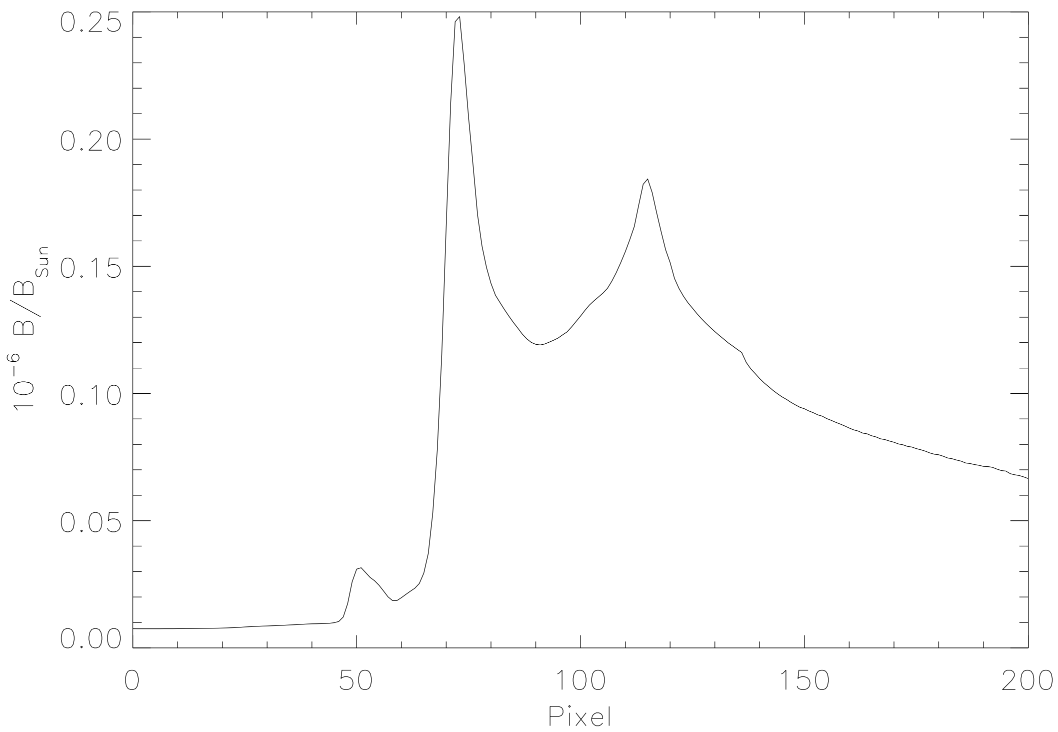

Figure 9: The estimated scattered light level as a function of radial distance. The actual levels may be a factor of 10 greater than this—see Section 6.5.

3.3×10^5 DN/pixel/sec. When we fold in the fact that the data was taken with an extinction level of 10^{-6} from a pair of neutral density filters, the true level of the source must be 3.3×10^{11} DN/pixel/sec. When we apply this factor to the measured B values shown in Figure 7, we get the average profile shown in Figure 9. The results are a factor of 10 *lower* than expected, which indicates that there may be a problem with the calibration procedure, possibly relating to the neutral density filters. Several different calibration methods were used durin the HAO tests, and were in good agreement with each other, and so those results are more reliable.

6.5 Source brightness

We measured the source brightness in two ways. One was to use the photodiode that was originally intended to be placed next to the instrument, while the other was with a Gamma Scientific photometer. Both measurements were made with bandpass filters identical to the one inside the ETU. The source brightness measurements were 10.5 and 7.5 W/m^2 respectively. This 40% discrepency was also seen in the HAO measurements.

From these measurements, we can estimate how many counts should be seen on the detector. The relevant parameters are shown in Table 1. Since we took the photometer measurements with

Table 1: Parameters used in calculation of expected signal level on detector.

Parameter	Value	Explanation
hc/λ	2×10^{-16}	Photon energy
C	68	Concentration factor, calculated as the ratio of the aperture area (radius 18 mm) to the image of the source on the detector (radius 2.18 mm)
F_g	0.645	Geometric factor due to the Lyot stop and spot
T_p	0.45	Transmission factor for unpolarized light through the polarizer
Q	0.55	Detector quantum efficiency
A	5.76×10^{-10}	Pixel area, in m^2
d	5	Camera digitization, in electrons/DN

The expected signal level then is

$$S = \frac{F \times C \times F_g \times T_p \times Q \times A}{(hc/\lambda) \times d}$$

If we use the photometer measurement of $F = 7.5$ W/m^2, we get $S = 3.3 \times 10^{10}$ DN/pixel/sec. Interestingly enough, this is almost exactly the value that you need to make the NRL results consistent with the HAO results. With this brightness level, the values in Figure 9 would be exactly a factor of 10 higher.

7 Conclusions

Overall, the results from the NRL tests confirm the results from the earlier ETU tests at HAO. There's some confusion about the absolute scattered light level—one method gives values a factor of 10 *lower* than those measured earlier, while another method is consistent with the earlier results—but there's no indication that the scattered light levels have increased. We were also able to confirm that the scattered light outside the occulter shadow is slightly polarized at the 0.5–3.0% level. The motion of the image due to the polarizer wedge was measured, and its effect on the derived polarization was explored. We found that the residual polarization in the unocculted field cannot be attributed as an artifact of the image motion. The correct functioning of the focal plane mask was confirmed.

It should be remembered, though, that the main purpose of the NRL tests was not to characterize the ETU, but to shake down the use of the NRL facility. What are the lessons learned from this exercise? They can be summarized as follows:

- Proper functioning of the GSE mechanisms will need to be confirmed before installing the instrument in the vacuum tank.
- Better procedures need to be worked out for monitoring the GN_2 purge, with clearly defined responsibilities.

- Although in many ways it's much easier to work on the optical bench outside the vacuum chamber, one disadvantage is that a separate steering system is required. In particular, when the NRL collimator is used during the COR1 flight assembly in Building 5, the collimator mount will need to be adjustable both spatially and tip-tilt.

- It's essential that the light source be monitored during all exposures, so that accurate polarimetry can be done. For the lamp illuminating the vacuum chamber, the entire lamp output must be monitored. This will be challenging, but may be accomplished with a beam splitter.